WHY ARE SEP NOBLE GASES SO ABUNDANT IN EXTRATERRESTRIAL SAMPLES?

Rainer Wieler, ETH Zürich, Isotope Geology, NO C61, CH-8092 Zürich, Switzerland. Wieler@erdw.ethz.ch

In the past 25 years evidence has steadily grown that besides the well-known solar wind (**SW**) a second "high-energy" component of solar noble gases is present in lunar soils and gas-rich meteorites [1-8]. However, an old problem with this **SEP** component remains: it accounts nominally for ~20-50% of the total solar noble gases in minerals and also in many bulk samples, whereas one might expect ions with energies >0.1 MeV/amu to contribute perhaps 10^{-4} - 10^{-5} to the total flux of solar particles [2]. Loss or redistribution of SW cannot account for the large SEP fractions of the heavy noble gases in lunar bulk samples, *if* the regolith as a whole has retained essentially every solar Ar, Kr, and Xe ion that ever hit the lunar surface, as is suggested by noble gas amounts in the regolith and the similar Ar/Kr/Xe ratios in bulk samples and mineral separates. I discuss the assumptions underlying this reasoning.

The SEP component is isotopically heavier and resides at larger depth than the SW. It has been reported for all five noble gases and in many mineral species with completely different noble gas diffusion properties. For most minerals, preferential diffusive loss of the surface-sited SW may explain relative SEP enhancements. An apparent SEP enrichment also results if SW loss and concurrent migration towards the grain interior is so large that the remaining SW becomes isotopically heavier than its true composition [9]. Both explanations are not feasible for Fe-Ni, where elemental ratios as function of grain-depth do not indicate that noble gas migration was important [8]. Even for Fe-Ni a relative SEP enrichment by orders of magnitude might be explained by other surface-loss processes like sputtering or terrestrial weathering, which certainly occurred in lunar mineral grains [10] and some gas-rich meteorites, respectively [11]. A cover of the investigated grains by (sub-)micron-sized dust [12] would also deplete the SW component more efficiently than the SEPs. All these explanations are not relevant, however, for a system without solar gas loss. The lunar regolith appears to be such a system.

Geiss [13] caluclated that the Xe amounts in the Apollo drill cores correspond to a solar irradiation during 2.6 Ga. He suggested that the average SW flux in the past ~4Ga has probably been considerably larger than today, because the regolith is several times deeper than the sampled 2.4 meters and because Xe might be depleted in the SW. Modifying Geiss' assumptions (Xe is enriched in the SW about four times [14, 15], and the mean SW flux at the Apollo sites is ~10% of the true flux at 1 AU, e.g. [16]) leads to times of ~1.7 and 2.1 Ga needed to fill the Apollo 15 and 16 cores, respectively. Considering uncertainties about mean regolith depth and gas concentrations in its lower portions, I conclude that the Xe amounts in the cores require an average flux of solar particles in the past ~4 Ga equal to or perhaps a few times higher than today. In other words, the data are consistent with the assumption that the heavy solar noble gases are well retained in the lunar regolith, though not necessarily in their original trapping sites.

The Ar/Kr/Xe ratios provide further evidence that the lunar regolith has not lost very much of the heavy noble gases. In-vacuo etch runs and single-grain studies indicate that mineral grains conserve the true Ar/Kr/Xe ratios in the SW [14, 15]. Composite particles in bulk samples dominate the solar noble gas concentrations in the regolith, and bulk samples generally have very similar Ar/Kr/Xe ratios as minerals separated from them. Hence, Ar, Kr, and Xe would have to leave the moon equally efficiently. Except for He, noble gases are lost non-thermally from the lunar atmosphere [17], depending on element-specific factors as scale height, ion trajectories and ionisation cross sections. It seems unlikely that this would not fractionate the elemental abundances, particularly since in the Manka-Michel process [17] the probability of an ion to hit the lunar surface is on the order of 50%, such that many cycles would be needed to obtain depletions of orders of magnitude.

Taking the nominal SW-Kr and SEP-Kr endmember compositions deduced from in-vacuo etch studies of lunar ilmenites [5], the SEP fraction in bulk samples usually accounts for between 10 and 40% of the total solar gas (a similar range is obtained for Xe, but I use Kr to bypass the question whether or not Pu-fission-Xe mimicks SEP-Xe [18]). The nominal SEP-Kr fraction in lunar bulk samples is thus similar to that in mineral separates, but cannot be explained by any mechanism discussed above, *if* the moon retains most or all solar Kr it ever trapped. In this situation, it may be tempting to hypothesize that the flux of particles representing SEP in lunar and meteoritic samples accounts for some tens of percent of the total solar flux. However, this hypothesis is very uncomfortable also, because such a high flux of suprathermal particles should have been observed by space scientists. I therefore now examine the assumptions above.

a) The SEP component is an artifact, due to i) inward migrated SW gas or ii) larger penetration depths of the heavier isotopes. This is very unlikely. In case i) we would then also expect large enrichments of the heavy elements in the grain-interiors, which are not observed for any mineral (5, 6, 8, 14). Furthermore, $^{20}Ne/^{22}Ne$ ratios as low as the SEP value of 11.2 cannot be obtained by diffusion/migration [9]. For case ii), we would not expect the observed uniform SEP endmembers in many different minerals, sometimes in a large number of consecutive etch steps [2]. This can be shown by simulations of ion-stopping in solids with the TRIM code [19]. If surface sputtering is taken into account, for Ne ions with a uniform SW velocity, the correct $^{20}Ne/^{22}Ne$ ratio of the SW (13.8) is observed at the grain surface, but this ratio drops to values considerably below the SEP value of 11.2 at larger depths (e. g. 500 Å), where, however, still sizeable Ne concentrations are expected (without sputtering, the $^{20}Ne/^{22}Ne$ ratio at the grain surface would rather be around 16). Case ii) is also extremely unlikely because etch parameters as step duration and acid temperature indicate that the depth of the SEP component

WHY ARE SEPs SO ABUNDANT?: R. Wieler

exceeds the few hundred Angstroms of the SW by orders of magnitude. In summary, the evidence for the reality of SEP as an independent component is firm.

b) SW-Kr and/or SEP-Kr are isotopically heavier than the assumed values. I take as endmembers the trapped Kr compositions [5] in steps from on-line etch runs that contain pure SW-Ne and SEP-Ne, respectively, as defined by many experiments [2, 4]. It seems not likely that pure SW-Ne or SEP-Ne is not accompanied by the more or less pure respective Kr endmember, although the nominal Kr values are somewhat different in the two ilmenite data sets available. The isotopically lighter SW-Kr preferred by Pepin and coworkers [18] would lead to even larger nominal SEP fractions. It might be that on-line etch experiments yield systematically too light isotopic compositions for one or both components, but at least for Ne there is experimental evidence to the contrary: $^{20}Ne/^{22}Ne$ ratios measured for the recent SW [13], including the new SOHO data [20], agree well with those deduced for SW-Ne in the whole variety of extraterrestrial samples [4, 8], and the SEP-Ne compositions in the many different samples also agree well with each other [2-4, 6, 8] It seems thus unlikely that the true Kr endmembers are very different from the assumed ones, although data on recent SW-Kr are certainly desirable.

c) Most of the solar Kr - preferentially the SW-Kr - has been lost from the moon, contrary to our assumption. This would require a solar particle flux much stronger than today at some time after the present-day regolith started to accumulate solar gases, i. e. certainly after the end of the T-Tauri phase. This is perhaps not impossible, but I discussed above that it is unlikely that the required gas losses would not have led to fractionated elemental abundances in bulk samples. Note that the Kr/Xe ratios in mineral separates cannot be fractionated values reflecting element-specific reimplantation efficiencies, rather than the true SW abundances as we concluded [14, 15], because in ilmenite grains the Kr/Xe ratio remains constant from the very surface to deeper layers which are not reached by reimplanted species. A loss of solar Kr has been postulated because N in lunar samples (assumed to be solar) is several times overabundant relative to Kr [21, 22]. This would probably mean that N and noble gases went through many reimplantation cycles, whereby N had a larger sticking probability. However, this conflicts with the argument that Kr and Xe in the minerals are not fractionated, which would not be expected in reimplantation scenarios, as noted above.

In summary, none of the explanations discussed for the high apparent fraction of SEP-Kr - and other SEP noble gases - is convincing. The SEP component is no artifact, and many arguments suggest that it represents a higher flux than is provided by the solar energetic particles in the MeV/amu range studied by space physicists. One of these arguments, not further discussed here, is based on the large amounts of SEP-Ne in meteoritic iron-nickel [8, 6]. It is very unlikely, however, that SEPs truly represent several tens of percent of all solar particles, as apparent solar Kr amounts in the lunar regolith might suggest. Crucial further experiments include determinations of solar Kr and Xe in gas-rich meteorites, measurements of the present-day isotopic composition of solar Kr and analyses of the N/noble-gas ratio in single lunar grains and as a function of grain-depth.

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